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Evaluation of AACMM using the virtual circles method

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Abstract

Articulated Arm Coordinate Measuring Machines (AACMMs) require a fast and reliable evaluation methodology and gauge at reduced cost. In this work, a gauge with virtual circles is presented and a study of its reliability is carried out. The studied parameters include the center error and the standard deviation of the center, diameter and distance. Two metrological laboratories have participated in the work and evaluation tests were performed independently with their own AACMMs but using the same methodology and equivalent gauges. The two AACMMs have a similar kinematic model and range but different accuracy according to manufacturer specifications. In a complementary test, two distances, 500 and 920 mm approximately, have been measured and analyzed in order to determine their suitability. Results have proved such gauge as a way for AACMM evaluation and distance is not a clear significance except for work volume evaluated.

Key words: Virtual circle; AACMM evaluation; Accuracy; Evaluation gauge

1. Introduction

Over the last decade, AACMMs have supposed a productivity improvement of inspection tasks where the highest level of accuracy is not required. Portability and flexibility gained with AACMMs development characterize their performance but also affect to their calibration and uncertainty evaluation. Calibration and evaluation methods and gauges, used for it, have been inherited from CMM field but AACMMs require new approaches according to their characteristics and kinematic structure. Some basis, such us gauges with sphere or

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conic holes, multiple gauge positions within the arm work volume or optimization methods, have been established previously by author works. Nevertheless, international experts have not clearly accepted a method or a gauge for these tasks.

Several calibration and performance evaluation methods have been proposed so far. Santolaria et al. (2008) presented a complete calibration method with a ball bar gauge where the error terms, volumetric accuracy and point repeatability are minimized by least squares. Furutani et al. (2003) also measure a two-ball bar in several spatial positions, the distance error was considered for the calibration. Kovac et al. (2003) designed a linear instrument for AACMM calibration. Several standards have proposed uncertainty evaluation methods, but they provide with highly time consuming processes. ASME B89.4.22 (2004) standard defines an evaluation method based on three tests to measure the AACMM uncertainty with a ball bar and a conic holes gauge. VDI/VDE 2617 part 9 (2009) evaluates AACMMS with three tests and a ball bar and conic holes as well. Spheres are commonly used in literature and industry for calibration, Cauchick-Miguel et al. (1996), despite that they are uncomfortable features for manual measuring with AACMM. Regarding to conic holes, they are adapted to AACMM manual control since the sphere of the stylus is easily placed on the cone and theoretically only one point is measured. Standards and some authors take advantage of this particular characteristic for the repeatability evaluation of a single point error when varying the AACMM pose , ASME B89.4.22 (2004) and VDI/VDE 2617 part 9 (2009a). Gao et al. (2009b) calculate the AACMM kinematic parameters by mean of neural networks and conic holes.

Piratelli et al. (2009) combined spheres and conic holes in a ball bar gauge. A virtual sphere was defined by four conic holes, four points, and a performance test (based on the ASME B89.4.22 (2004)) designed in order to reduce the cost of the gauge and evaluation time. Thereby, not only a single point is considered for AACMM uncertainty but also the variability of the diameter of the sphere and distance between centers. This concept of virtual spheres was also implemented in a plate, Piratelli et al. (2012). A similar gauge is presented in this paper and a further analysis carried out. Virtual circle gauge is suggested in order to evaluate the reliability of AACMM. This work pursues to reduce the cost and required time for AACMMs evaluation by eliminating redundant input. In previous work, authors remarks the high influence of the operator by measuring a master piece based on "metrological features" ,Cuesta (2012), but conic holes seem to offer a high repeatability for these instruments. In addition, two AACMMs, provided by two metrological laboratories (Laboratory 1: University of Oviedo and Laboratory 2: University of León), are evaluated.

2. Methodology

Precision spheres require a thorough manufacturing process and according to their precision grade the cost increases. These spheres are usually used for calibrating CMMs, AACMMs, probes or optic systems among others due to their well known parameters. Virtual spheres avoid spheres manufacturing, so cost is reduced considerably. In addition, spheres have to be attached to the gauge (bar) somehow and this process could deform the sphere. Virtual spheres can be manufactured directly on the bar so assembly is not required. On other hand, conic holes are particularly useful for AACMM measuring characteristics. While CMM is unable to fit the ball stylus into the conic hole, the manual control of AACMMs allows to place the stylus ball into the conic hole with a stable contact. Piratelli et al. (2009) proposed the virtual sphere as a fast and low-cost method for AACMM validation. Instead of a virtual sphere, it is considered that virtual circles can determine the AACMM uncertainty without redundant data.

Two gauges, Fig. 1, were manufactured in a CNC milling center. One was assigned to Lab 1 and the other to Lab 2. Both specimens were machined from a hard aluminium alloy with a subsequent hard anodized treatment. Gauges have an inverted-T shaped with a total length of 1000 mm, covering the measuring ranges of the available AACMMs. Three points given by conic holes (drilled with a center-drill tool and with enough depth to accommodate the probe ball) are located on the bar in order to define a virtual circle. Gauges have four sets of virtual circles that materialize two distances, approximately 500 mm (circles 1 and 2) and 920 mm (circles 3 and 4). The diameter of any virtual circles of each gauge does not require calibration because only the dispersion between several measurements is taken into account, avoiding the use of a "reference" center position, Piratelli et al. (2009). An auxiliary device, designed for gauge multi-positioning and with minimum structural deformation, was also developed and manufactured.

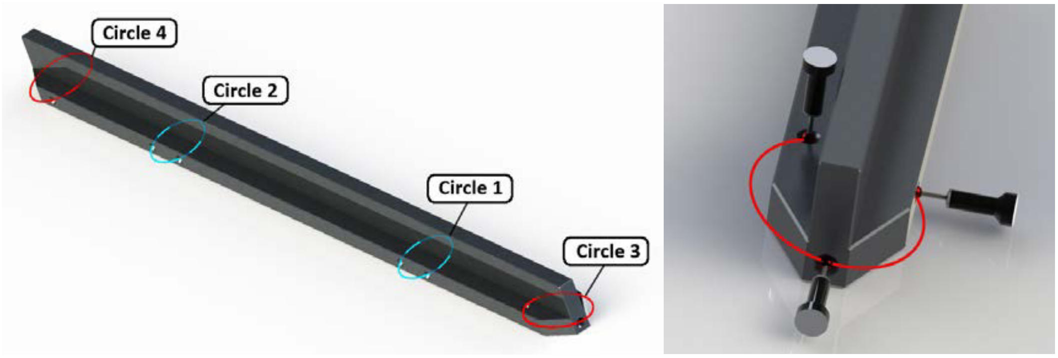


Fig. 1. Virtual circle gauge and the virtual circle representation.

2.1. Test methodology

Each laboratory owns an AACMM with different technical characteristics, Table 1. The AACMMs uses the same model of contact probe, a rigid probe with a 6 mm ball stylus. Since they have the same kinematic model and range, the gauge length is suitable for both AACMMs and the results are comparable. Only accuracy and the operator differ from both AACMM tests.

The repeatability error and length accuracy are manufacturer specifications (Hexagon Metrology®). The 'Sphere test' consists in the measurement of a calibrated sphere by an operator. The collected point's data is used to calculate the center of the sphere with the best fit method. Thereby, this repeatability is the distance between each contact point and the sphere center minus the theoretical radius. The output of the 'Cone test' is the standard deviation of points measured with a conic hole from multiple approach directions. Finally, a gage block is measured several times throughout the working volume for 'Length Accuracy test'. The output is the standard deviation of the distance minus the theoretical length.

Table 1. AACMMs technical specifications

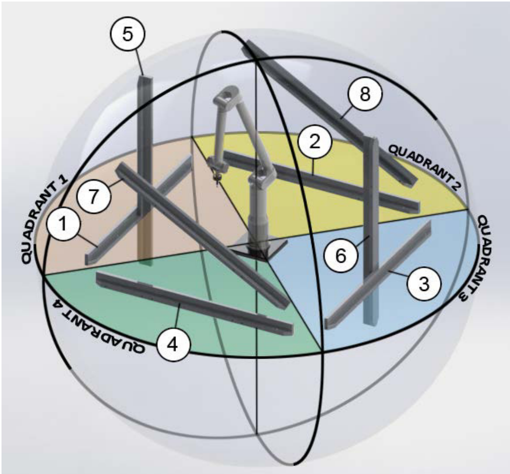
	Laboratory 1 /AACMM 1	Laboratory 2 / AACMM 2
Model	Romer Sigma (6 DOF)	Romer Omega (6 DOF)
Range [mm]	1800	1800
Repeatability, Sphere test [mm]	0.010	0.020
Repeatability, Cone test [mm]	0.018	0.036
Length Accuracy [mm]	0.025	0.050

From evaluation standards and other author's works a complete analysis of the accuracy throughout the working volume is necessary for AACMM evaluation. ASME establishes 20 spatial positions of the gauge combining horizontal, vertical and inclined positions but it takes excessive time. Piratelli et al. (2009) makes use of design of experiment to reduce to 9 positions. VDI standard locates the gauge in 7 positions. For this test, 8 positions have been defined, Table 2. This test includes 4 horizontal, 2 vertical and 2 inclined gauge positions. The quadrant is given by the AACMM position that is simulated by the gauge transporting and the change of its relative position to complete the volume study.

A complementary test has been implemented in order to evaluate the influence of the distance between the virtual circles. The gauge of the laboratory 1 includes a total of 4 virtual circles: two at the ends of the gauge and two others. Therefore, two distances are available for the evaluation.

Table 2. Test positions

Position	Gauge	Quadrant (AACMM position)
1	Horizontal	1
2	Horizontal	2
3	Horizontal	3
4	Horizontal	4
5	Vertical	1
6	Vertical	3
7	45°	2
8	45°	4



2.2. Test setup

The test setup consists on a stable surface where the AACMM, a gauge positioning instrument and the gauge are mounted. A rigid work-table was built for laboratory 1; it contains several plaques that allow the AACMM and part fixtures mounting as CMM tables. Laboratory 2 stable surface is a CMM marble table. As mentioned before, a gauge positioning instrument was also developed; it is composed of a base, a column (for a comfortable measuring height), a mechanism that determines and assures the relative position of the gauge and a support for the gauge.

During measurements, PCDMIS® software collects the coordinates of center of the ball stylus of the AACMM. Later, data are transferred to a MATLAB® file for subsequent processing. Virtual circles are constructed and the value of the center coordinates and diameter obtained. The distance between the virtual circles centers is also calculated. Repeatability in center coordinates, diameter and distance is measured 15 times for each virtual circle and gauge position (at least 10 repetitions after outliers processing). A minimum of 80 measurements are taken for each virtual circle. The temperature of the environment is controlled within 20 ±1 °C.

The same setup is followed for the complementary test, distance between virtual circles. The operator of Laboratory 1 measures both sets of virtual circles, 15 times per virtual circle and position and, after outliers processing, the results of 10 repetitions remains, at least. A minimum of 80 distances are taken for each pair of virtual circle.

3. Test results

From the gauge measurement, three data sets show the precision of the AACMMs: center coordinates error, diameter error and distance error. The mean value of the center coordinates for each position is the reference center and the error is calculated as the distance from each point to such center. Fig. 2a shows the results of the measurement of circle 1 at laboratory 1. The diameter error is the diameter calculated for each repetition minus the mean diameter of the measurement of each position. Fig. 2b shows the results of the measurement of circle 1 at laboratory 1.

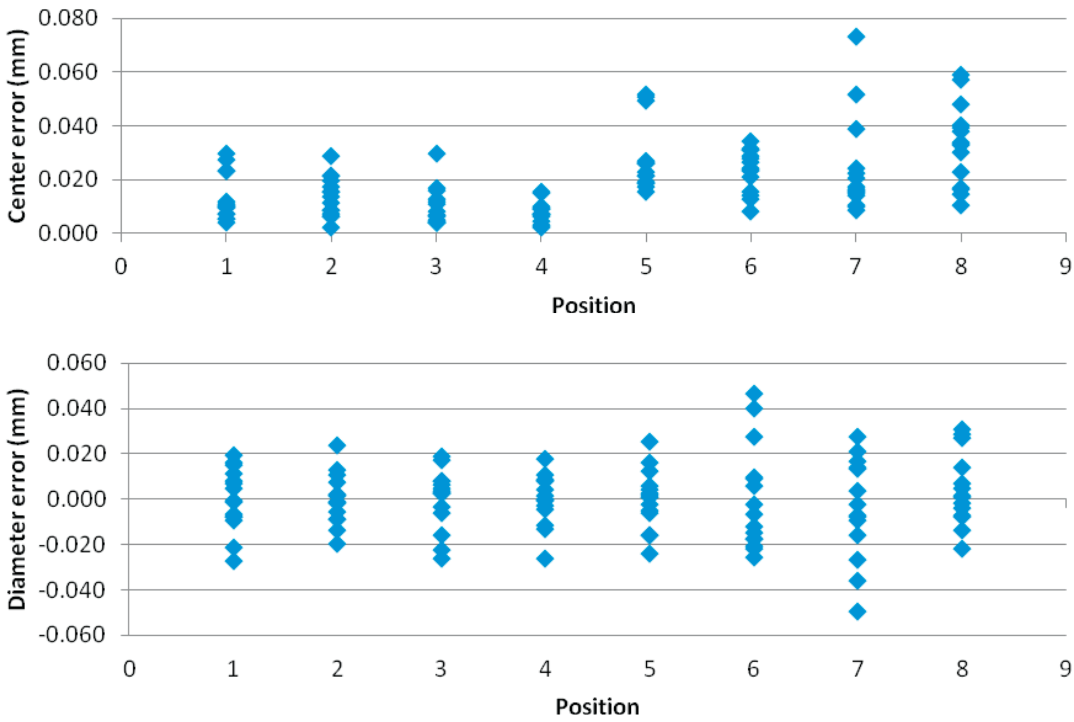


Fig. 2. Center error and diameter error for circle 1 measurement at Lab 1

Distance error corresponds to the distance between the two virtual circles of the gauge. The mean of the distance for each position is the reference value for errors comparison. Fig. 3 shows the distance error for the distance between circle 1 and 2.

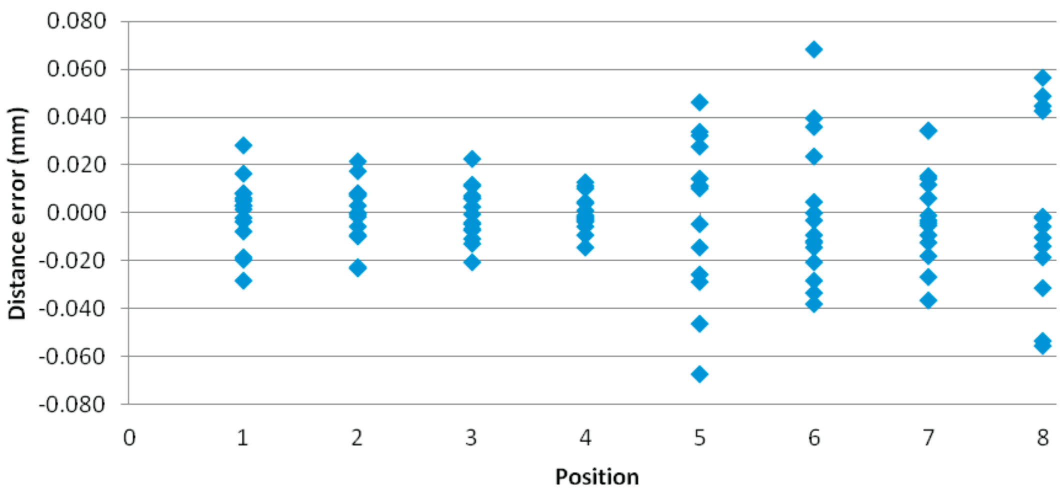


Fig. 3. Distance error for circle 1 and 2 measurement at Lab 1.

Outliers that result from wrong measurements have been eliminated by Chauvenet criteria on the point coordinates. Although it has been observed that the variability of AACMM measurements contrast with a strict Chauvenet method, especially in the measurement with low standard deviation. Because of that, Chauvenet has been applied to measurement with a standard deviation higher that the AACMM accuracy provided by manufacturer. Thereby, measurements with low standard deviation are maintained and measurements with high standard deviation are processed. Additional measurements are carried out in order to achieve at least 10 repetitions per position.

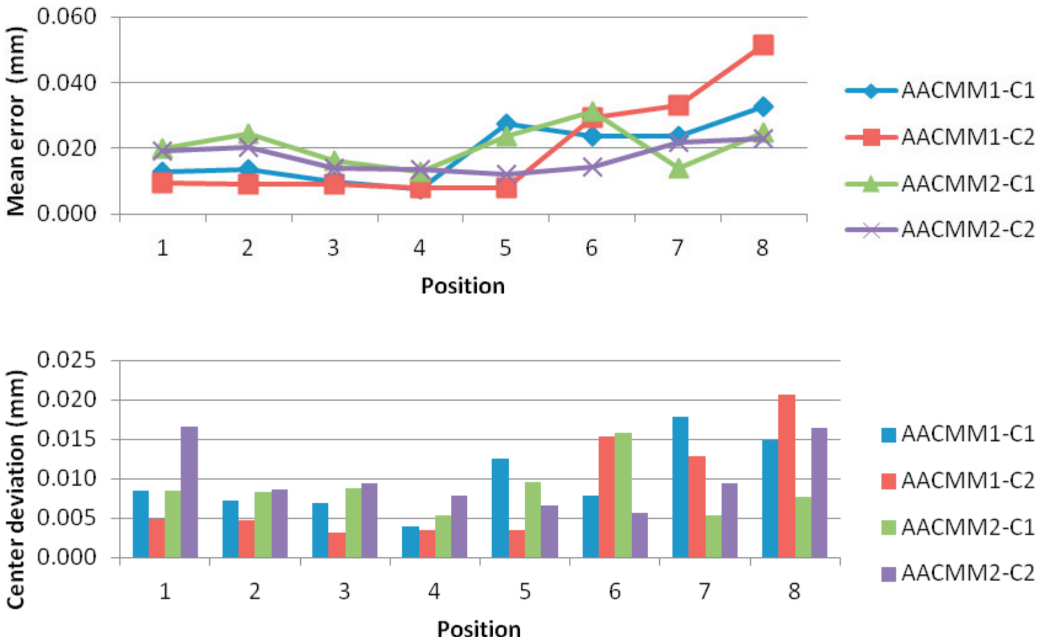


Fig. 4. Center error and standard deviation for evaluation test.

3.1. AACMM evaluation test

From the above mentioned data the mean error of the diameter and standard deviation are obtained are calculated and represented for each position. The total standard deviations of 0.0136 and 0.0181 mm and ranges of 0.0709 and 0.0828 mm for test in laboratory 1, circle 1 and 2 respectively result from the measurements. In laboratory 2, measurements obtains standard deviations of 0.0107 and 0.0116 mm and ranges of 0.05601 and 0.0610 mm. Fig. 4 shows the variation of the center error and its standard deviation throughout the positions.

Fig. 5 shows the diameter standard deviation for both virtual circles and laboratories. The mean diameters of the gauge of the laboratory 1 are 65.4301 and 65.3713 mm (circle 1 and circle 2 respectively) and 65.502 and 65.391 for laboratory 2. The total standard deviations found for laboratory 1 are 0.0155 and 0.0221 mm in circle 1 and 2 respectively and ranges of 0.0959 and 0.1221 mm. In the laboratory 2 the standard deviations are 0.0201 and 0.0145 mm and the ranges are 0.1056 and 0.0753 mm.

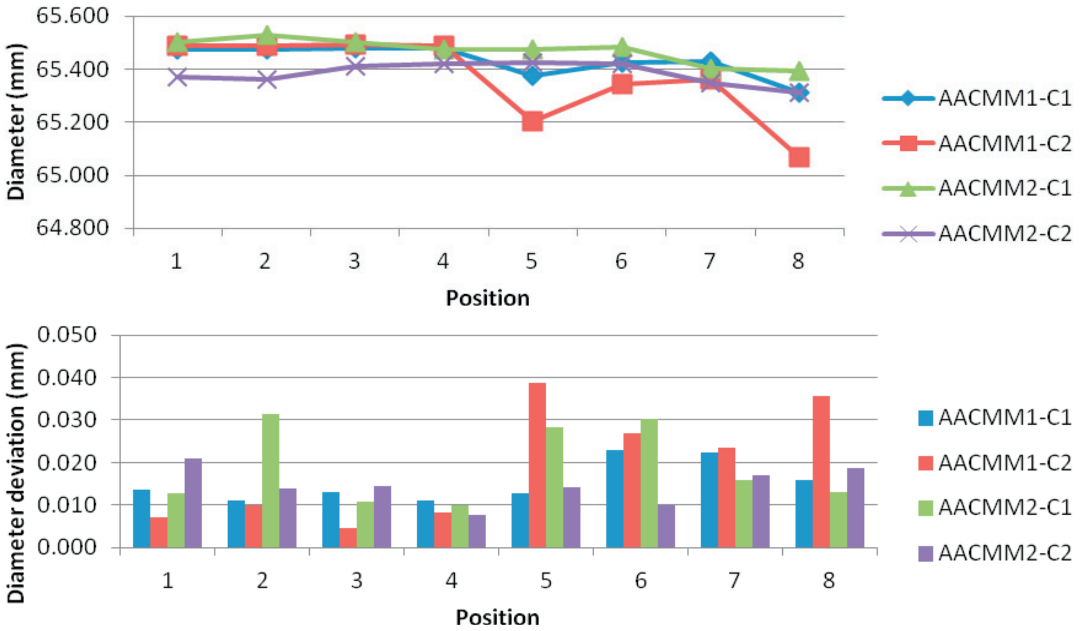


Fig. 5. Diameter and standard deviation for evaluation test

Fig. 6 shows the standard deviation of the distance for each gauge. The total mean distances are 500.008 and 499.990 mm for gauges at laboratory 1 and 2 respectively. A standard deviation of 0.0221 mm and a range of 0.1358 mm for test in laboratory 1 and a standard deviation of 0.0212 mm and a range of 0.104 mm for test in laboratory 2 are obtained.

Fig. 6. Distance error and standard deviation for Lab 1 and Lab 2 for evaluation test

3.2. Distance comparison test

As before the mean values for each position are used as the reference values. The short distance (Circle1 to Circle2) is 500.008 mm and the long distance (Circle3-Circle4) is 921.825 mm. The short distance has a standard deviation of 0.0221 mm and a range of 0.1358 mm and the long distance has a standard deviation of 0.0255 mm and a range of 0.1480 mm. Fig. 7 shows the standard deviation of the distance measurements.

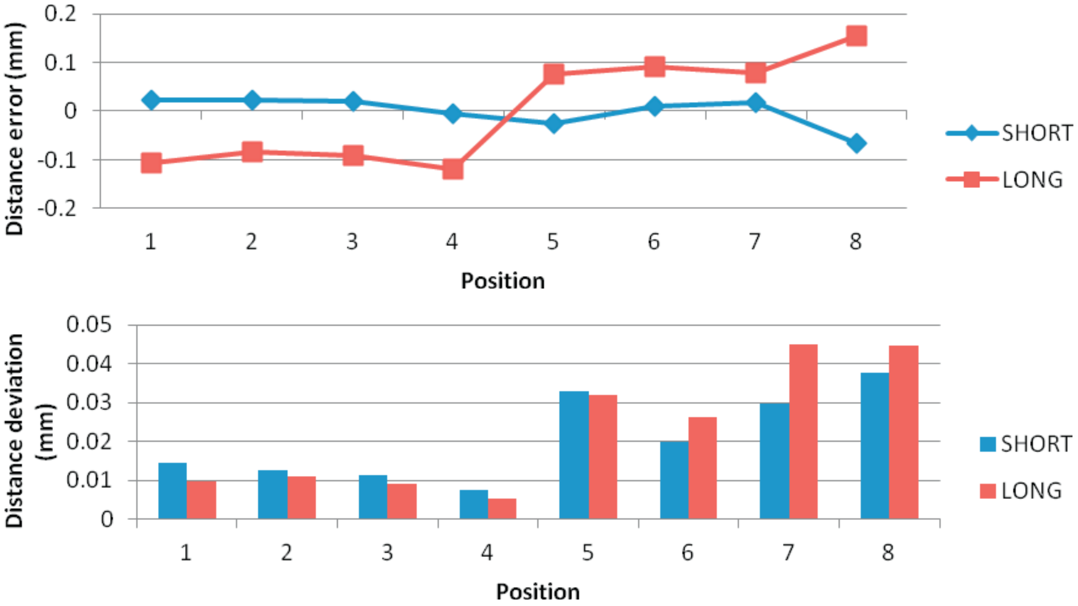


Fig. 7. Distance error and standard deviation for short and long distance at lab1.

3.3. Test results analysis

Before the virtual circles construction, the standard deviation of each point in the conic holes remains within the repeatability of the ‘Cone test’ from manufacturer specifications (0.010 and 0.018 mm). The standard deviation of the center of virtual circles also remains around the repeatability of the ‘Sphere test’. The diameters obtained by the AACMM seem to not be affected by the position but circle 2 of the laboratory 2 has a significant variability than the rest of circles. The diameter standard deviation is within acceptable limits but the standard deviation of some positions could be improved.

In relation to the distance, the positions affect to absolute value the laboratory 2 deeper than to the laboratory 1. Laboratory 1 has a total standard deviation under the ‘Length test’ limits but some individual positions provide with a higher standard deviation. Laboratory 2 agrees with this test. Finally, although the short and long distance have a similar standard deviation, the short distance values have a lower variability of the positions distances.

According to the AACMM evaluation test results, it has been noted that positions 1,2,3 and 4 gives the best results in terms of errors and standard deviation although most of the results are in agreement with the technical specification, as well. The worst behaviour for the rest of the positions could be explained by the gauge positions that force to measure in an uncomfortable and unstable operator pose. It also can be because of extreme positions, near to the AACMM limits.

The test duration is less than an hour and it decreases with the operator’s skill and experience.

There seems not to be a clear difference for distance standard deviation between laboratories in the distance test but the reference values for each position has a lower variability in the laboratory 1 case. Although both instrument met the technical specifications in most of the measurements, laboratory 1 obtained a better performance throughout the evaluated positions, as expected. Again, this behaviour can be explained by the extreme position, near to the work volume limits.

4. Conclusions

The virtual circle gauge has been used for AACMM evaluation successfully. Data obtained by the evaluation test using the virtual circles method provide enough information that can be compared to manufacturers' specifications. The proposed methodology and gauge make use of a low-cost gauge and a fast and reliable methodology.

The distance between two circles has not a clear influence in the standard deviation of the measurements but the long distance value affect to the reference distance of each position of the gauge. In contrast, the longest distance assures the evaluation of the complete work volume of the AACMM.

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